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WITNESS my hand this
Eighth day of October 2003

J R Yabsley

JONNE YABSLEY
TEAM LEADER EXAMINATION
SUPPORT AND SALES

PRIORITY DOCUMENT
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AUSTRALIA

Patents Act 1990

PROVISIONAL SPECIFICATION

Applicant(s):

CRC FOR INTELLIGENT MANUFACTURING SYSTEMS
& TECHNOLOGIES LTD
A.C.N. 060 244 537

Invention Title:

REFLECTOMETRY

The invention is described in the following statement:

REFLECTOMETRY

This invention relates to improvements in optical time domain reflectometry and more particularly relates to a distributed temperature sensor and its method of operation.

A distributed temperature sensor (DTS) measures temperatures along an optical fibre that is located in thermal contact with an object to be measured and functions in a manner similar in principle to that of RADAR and SONAR. In RADAR, the total time an electromagnetic probing pulse takes in its journey from the source to a distant object and its reflection takes to return to the origin together with the known speed of the electromagnetic wave allows the location of a distant object to be deduced. In SONAR an acoustic probing signal is employed. In DTS systems a very short pulse of laser light (less than 100 ns) is the probe. After leaving the laser the light pulse (probe) travels through an optical fibre to an optical coupler and into the sensing fibre. As the light pulse travels along the sensing fibre, a small fraction of the incident pulse is absorbed by the fibre atoms and the pulse intensity is attenuated.

Of the several absorption processes that take place the fundamental limit to transparency is Rayleigh scattering and is given by:

$$\alpha \propto \frac{1}{\lambda^4}\left(n^2 - 1\right)kT$$

where α is the absorption loss (1 to several dB/km), λ is wavelength, n is the refractive index, k is Boltzmann's constant and T is the temperature.

It is the Rayleigh scattering that limits the sensing range. The attenuation process also involves relatively weak interactions between the probing pulse and the glass molecules that changes the wavelength of the light. These various interactions cause light to be scattered from the molecules - some of this scattered light travels back towards the proximal of the fibre as light of the original wavelength (Rayleigh) and some as light of different wavelengths (the Raman components). The different spectral components are illustrated in Figure 2. The back scattered power received for Raman scattering at a particular wavelength λ_r is given by

$$P_r \propto \frac{1}{\lambda_r^4[1-\exp(-h\nu/kT)]}$$

where h is Planck's constant and ν is the frequency shift of the scattered light. Thus, while most light energy is transmitted in the forward direction along the fibre, a small fraction of it is sent backwards, where it may be detected and analysed.

In general, the accurate derivation of quantities based on the measurement of light intensity is most conveniently made through the measurement of light intensity ratios, because the absolute intensity (or power) is difficult to measure accurately. The intensity of an optical signal can be influenced by a large number of variables in addition to the quantity of interest. For example, the power output of the source, the efficiency of the detector and the efficiency of the optical elements can all be effected by changes in temperature. These effects can be difficult to predict and model reliably. Alternatively, the effects can be reduced through the provision of a stable thermal environment and suitable calibration means. In the art, it has been argued that a combination of these approaches (ratiometric and calibration) provides the most practical and efficient solution to obtaining accurate measurements of temperature distribution, given all of the various sources of uncertainty that apply.

The method of detection and analysis varies between different DTS embodiments based on glass optical fibres. In the earliest embodiments, a diffraction grating was used to filter out a band of back-scattered wavelengths close to the laser wavelength (mainly the Rayleigh scattering). The Stokes and anti-Stokes Raman wavelengths were allowed to pass to separate detectors and the intensity ratio of these components was used to derive the temperature as a function of range in the fibre (see GB 2,140,554A).

An improved method was subsequently devised, whereby the Rayleigh scattering and anti-Stokes Raman scattering are selected for measurement by separate detectors (see GB 2,183,821A). These intensities are compared in a ratio device to give an indication of the temperatures in the fibre. It is claimed that this arrangement permits a much faster response than the prior art method, as the Rayleigh scattered light is much more intense than the Stokes Raman and can be sensed using relatively simple and inexpensive equipment.

In a further embodiment, a method was devised whereby a single spectral band of the backscattered radiation (usually a region of the broad anti-Stokes spectrum) is selected for analysis (see US 4,823,166). The method uses the ratio of the backscattered power to the probe pulse power at a given section of the fibre to deduce the temperature distribution. Effects of built in defects in the fibre may be eliminated by calibrating the fibre prior to installation with a known temperature distribution. The sensor then measures departures of the backscatter intensity from those determined at the time of calibration and interprets them in terms of a temperature variation. However, this approach restricts the system to use with fibres for which a calibration has been performed and requires recalibration if the fibre properties change. Short-term changes in the energy and wavelength of the source can be detected and corrected by monitoring a short reference section of the fibre that is held at a constant temperature in a temperature-controlled chamber. Provision is also made for the removal of the filter to facilitate measurement of the total backscatter signal in the reference section, or over the entire fibre length, so that a normalisation can be performed. It is claimed that the embodiment described in US 4,823,166 removes the need for corrections to be made for the difference in fibre attenuation between the Stokes and anti-Stokes wavelengths. It is also claimed that the system offers enhanced sensitivity to temperature changes, reduced sensitivity to drifts in the source wavelength and a simplified optical arrangement. However, the need to remove the filter to perform the normalisation procedure and the need to calibrate each fibre with a known temperature distribution over its entire length remain drawbacks for practical operation.

It is these issues that have brought about the present invention.

In accordance with one aspect of the present invention there is provided an optical time domain reflectometry method in which pulses of optical radiation are launched into an optical fibre and optical radiation back scattered from the fibre is detected to produce electrical output signals characterised in that the back scattered radiation is passed through a single optical filter at the anti-Stokes wavelength which records only the anti-Stokes signal and unwanted artefacts are removed by mathematical smoothing or the single optical filter records the quotient of the anti-Stokes signal divided by the Rayleigh signal where the Rayleigh signal is achieved by using a laser diode (LD) transmitter in a light emitting diode (LED) mode.

In a further aspect of the present invention there is provided an optical time domain reflectometry method in which pulses of optical radiation are launched into an optical fibre and optical radiation back scattered from the fibre is detected to produce electrical output signals, characterised in that the optical radiation is transmitted by a LD transmitter and the back scattered radiation is detected by counting photons through a single optical filter at the anti-Stokes wavelength which records only the anti-Stokes signal and unwanted artefacts are removed by mathematical smoothing or the single optical filter records the quotient of the anti-Stokes signal divided by the Rayleigh signal where the Rayleigh signal is achieved by using the LD transmitter in a light emitting diode mode.

Preferably, the optical time domain reflectometry method is used to measure temperature fluctuations along the optical fibre. In a preferred embodiment, at least one temperature sensor is positioned down stream of the connectors to account for error signals emanating from the connectors. The sensor is preferably a thermistor or thermocouple placed 20m (or some other convenient distance) down the optical fibre to provide a temperature indication and account for the influence of connector error.

The wavelength of the transmitted signal is preferably between the ultraviolet and infrared spectrum. The transmission power of the LD is preferably less than 10 W, usually less than 1 W.

An embodiment of the present invention will now be described by way of example only with reference to the accompanying drawings in which:

Figure 1 is a schematic illustration of the basic components of a distributed temperature sensor,

Figure 2 is a graph of light spectrum against wavelength illustrating the major spectral features and location of an optical filter,

Figure 3 is a graph illustrating an accumulated photon count,

Figure 4 is a circuit diagram relating to the LD driver electronics,

Figure 5 is an illustration of the operational amplifier (Op-Amp) output of the LD driver circuit with laser diode voltage and current waveform signals of 10 ns width,

Figure 6 is a schematic illustration of a distributed temperature sensor and temperature calibration means, and

Figure 7 is an illustration of the photon count using the calibration of Figure 6.

In the distributed temperature sensor (DTS) 10 shown in Figure 1 a very short pulse of laser light (less than 100ns) constitutes a probe. After leaving the laser 11 the light pulse (probe) travels through an optical fibre 12 to an optical coupler 13 and into the sensing fibre 14. As the probe pulse travels along the sensing fibre, a small fraction of the incident light is absorbed by the glass atoms and the pulse intensity is attenuated. An even smaller fraction of the incident light is scattered back along the fibre with the typical spectrum shown in Figure 2.

In the DTS's normal operating mode the band-pass filter 15 allows only the shorter wavelength anti-Stokes light to be detected. The total times taken for light to travel from the source to the point of scatter and for the scattered light to travel back to the detector are recorded at discrete intervals of 2ns (bins). It is the intensity of the returned light together with its time of arrival that allows the system to deduce the temperature profile along the sensing fibre. The process is repeated many thousands of times per second and the results are accumulated over a predefined period (typically minutes). Figure 3 shows a typical accumulated photon count result. The accumulated photon count as a function of position along the fibre is then downloaded to a central processing unit where the calculations to obtain a temperature are made. The DTS requires high-speed electronics for the LD driver and photon detection circuits but uses the essential advantages of the photon counting method to simplify all other aspects of DTS operation.

In summary the DTS monitors the back-scattered signal using:

- the photon counting method to record light intensity, and
- the arrival time to identify position.

The DTS distributed sensor 10 is characterized by:

1) A laser diode light source 11.
2) A photomultiplier light detector 16.

3) A 50/50 optical coupler 13.
4) An optical filter 15.
5) Temperature calibration system.
6) Analogue control circuitry.
7) High-speed laser driving circuitry.
8) High-speed photon detection circuitry.
9) High-speed photon counting and accumulation circuitry.
10) A CPU for control, data collection and processing.

The light probe 11 is generated by a Sanyo DL7140 785nm, 80mW (CW), single-mode, AlGaInP, index guide structure, solid-state laser diode. The electronic drive circuitry is shown in Figure 4. The drive circuitry allows for two LD operating modes: LASING and LEDing mode. A complete description of these modes is given below.

The DTS operates in a photon counting mode. The intensity of the light returning to the detector is sufficiently low as to comprise mostly of separate photons arriving at distinguishable times. The detection system represents each photon as an electrical signal that is digitally recorded as an event labelled with the time of arrival of the photon, measured from when the laser pulse was fired. Light to be recorded is selected with a single filter set at a central wavelength (CWL) of 755nm and a full width half maximum (FWHM) pass bandwidth of 10-20nm, a transmission of greater than 85% in the band pass and a rejection in the order of 10^5.

Figure 2 identifies three spectral components: the shorter wavelength anti-Stokes Raman (AS), Rayleigh (R) and the longer wavelength Stokes Raman (S). All these spectral components contain to varying degrees both temperature (T) and non-temperature (NT) information. The DTS challenge is to recover only the temperature information. Conventional distributed temperature theory provides that a temperature determination that is essentially independent of the NT effects can be made by taking the ratio AS/S or alternatively the ratio AS/R. The ratio of the amounts of light back-scattered into the two Raman bands is given by:-

$$R_r = \frac{Anti\ Stokes\ \ Intensity}{Stokes\ Intensity} = \frac{\lambda_l^4}{\lambda_s^4} \exp\left(-\frac{h\nu}{kT}\right)$$

and is thus a function of the temperature of the fibre at the scattering site.

In such cases measurements of light at two separate wavelengths are required. In some embodiments of this kind of technology all three spectral components are detected and recorded. In these cases there is an increase in system complexity and more, often costly components, are required. In addition, complicated corrections have to be made for the fact that the absorption loss in the fibre differs slightly at the two wavelengths and is also temperature dependent.

The DTS system described hereunder allows certain non-temperature dependant effects on the optical fibre to be measured in order to remove these effects from the final result. The NT effects are measured by means of the Rayleigh signal, which is relatively temperature insensitive. This procedure exploits the characteristics of a laser diode that are such that at low current the device behaves as a light emitting diode whilst at higher currents it has the properties of a laser.

The electroluminescence of the semiconductor laser and the light-emitting diode LED result from a current flow through a *p-n* junction to which a voltage has been applied. Recombination of the carriers injected across the junction results in the emission of light. A measure of the quality of this process is the quantum efficiency, defined as the ratio of the number of emitted photons to the number of electrons crossing the p-n junction. The spontaneous emission of LEDs is characterised by a low quantum efficiency and a relatively broad spectrum which is of little value as a light source to the basic distributed temperature system, however this effect is exploited in our claim. In the semiconductor laser both the electrons and the radiative emissions are confined by a cavity with partially reflective surfaces to produce stimulated emission. Stimulated emission in such an arrangement results when a photon with an energy slightly greater than the energy gap can interact with an electron in the conduction band and cause the electron to recombine with a hole in the valence band. This recombination process results in the emission of a photon identical to the photon that caused the recombination process, and the number of photons is increased. At

low current, the laser light intensity is small and results from spontaneous emission, as in a LED. However, when the stimulated emission exceeds the internal losses, the laser threshold is reached and the light output rises rapidly with the current. Above the threshold current, most of the current flowing into the p-n junction results in laser emission, and the quantum efficiency is much higher than for an LED and the emitted light is almost, but not quite monochromatic. This dual nature of semiconductor lasers is exploited in the present claims.

The principle of operation is:

1) Make a measurement with LD in LASER mode yielding a record of temperature and non-temperature data.
2) Make a measurement with LD in LED mode. In this case light passing through the filter is predominantly due to the Rayleigh effect and is not temperature sensitive.
3) Mathematically deduce a record from both signals that only reflects the temperature dependence.

This functionality is achieved through a novel circuit shown in Figures 4 and 5

The circuits features are:

1. Operation in LASER mode.
2. Operation in LED mode.
3. The probe pulse can be widened to increase the power so that better temperature resolution can be obtained.
4. An ability to control the current so as to produce a high-speed probing pulse for better range resolution.

Power Supply:

When the equipment is first turned on there is no power to the LD drive circuit. A 5V supply (labelled "+5V slow" in Figure 4) is applied a few seconds after other system circuitry is stable.

Quiescent circuit condition:

In the quiescent state, a bias (-V) is applied to the LD to provide a level of current just below the value required for light emission. Its function is to reduce the amount of current required to create light emissions and thereby reduce the magnitude of the voltage swing and slew rate required of the operational amplifier.

The LD is biased, in its normally off state, by being connected between the Op-Amp output (normally 0V) and –V. –V is chosen to be about –1.6V to maintain the LD just below its turn-on point. It is critical to keep the current very low in this state as "can" type LDs may act as extremely efficient LEDs at sub-milliamp levels. Further bias adjustment is provided by a resistor from +5V to the inverting input, particularly relevant for the period between steps 3 and 4 below.

Dynamic behaviour:

1 Dynamic events commence when a nominally 50 ns wide TTL positive-going trigger pulse is applied to the circuit. The shape of this pulse is not particularly critical and it does not define the circuit's output pulse width. This trigger takes two paths.

   a. The trigger signal is reshaped and delayed. The input trigger pulse is reshaped into pulses with faster rise times by the 10 Schmitt triggers connected in series and internal to the 50A-10250 TTL digital delay line integrated circuit package. Reshaped versions of the input trigger signal appear at successive outputs of this package each delayed by 2.5nS from the previous one.

   b. To improve the LD's turn-on-time a small bias current is applied to the diode prior to the application of the trigger signal from the delay line. This bias current is due to a small fraction of the input trigger pulse that is applied to the non-inverting input of operational amplifier (HFA1130).

2. In the circuit shown in Figure 4, one of the reshaped signals delayed by 2.5 ns (T1) is connected to non-inverting input of HFA1130 Op-Amp. At this point the inverting input source is still zero, and the amplifier output is large and positive. Current limit into the LD is provided by a combination of the Op-Amp Vh output limit and a 15Ω series resistor.

It should be noted that the HF1130 Op-Amp has two critical differences from other so-called "fast" Op-Amps. Firstly the HF1130 contains high and low output voltage limit circuitry (Vh and VL inputs) which prevent the internal circuitry from saturating. This allows very large gains to be used, which effectively improve the rise time of the output without the normally associated dampened response caused by saturation in other Op-Amps. Secondly, the HFA1130 output drive contains special high speed/current components with more in common to a Norton Amplifier than an Op-Amp. The output rise time is 6000 V/μs which is much faster than typical driver circuits with speeds of only 100-500 V/μs for low loads and small signals. All Op-Amp inputs comply with manufacturers recommendations for input impedance and circuit layout as far as practicable.

3. The second delayed trigger pulse is connected to the inverting input from the delay line. Any one of the delayed outputs (for example T7) can be used. The final output pulse width is determined by the time difference (for example T1-T7). This signal causes an inverted and greatly amplified output which reverse biases the LD and completely switches it off much faster then zero biasing would. The Op-Amp inputs have a common mode voltage of approx 2.5 V at this stage.
4. When the first delay line output returns to zero volts, but before the second output does, the diode (U16) between the delay line outputs conducts and briefly shorts them. This begins to switch off the LD reverse bias and removes an output glitch that would otherwise be present. A small signal silicon diode, such as the common IN914B, with high speed under these conditions is most appropriate.
5. Both delay line outputs have returned to zero volts and LD is returned to non-conducting state.

Since the voltage applied to the LD resistor circuit does not directly indicate the magnitude of the laser current, the LD current pulse is deduced from the potential across the resistor. This method better predicts the optical power output, the turn-on rise time, and makes visible the stored charge flowing in reverse direction from the LD during turn-off.

CLAIMS:

1. An optical time domain reflectometry method in which pulses of optical radiation are launched into an optical fibre and optical radiation back scattered from the fibre is detected to produce electrical output signals characterised in that the back scattered radiation is passed through a single optical filter at the anti-Stokes wavelength which records only the anti-Stokes signal and unwanted artefacts are removed by mathematical smoothing or the single optical filter records the quotient of the anti-Stokes wavelength divided by the Rayleigh wavelength where the Rayleigh wavelength is achieved by using a laser diode transmitter in a light emitting diode mode.

2. An optical time domain reflectometry method in which pulses of optical radiation are launched into an optical fibre and optical radiation back scattered from the fibre is detected to produce electrical output signals, characterised in that the optical radiation is transmitted by a laser diode transmitter and the back scattered radiation is detected by counting photons through a single optical filter at the anti-Stokes wavelength which records only the anti-Stokes signal and unwanted artefacts are removed by mathematical smoothing or the single optical filter records the quotient of the anti-Stokes wavelength divided by the Rayleigh wavelength where the Rayleigh wavelength is achieved by using the laser diode transmitter in a light emitting diode mode.

3. A method of measuring temperature fluctuations along an optical fibre, including the optical time domain reflectometry of either claim 1 or 2.

4. A method as claimed in any on eof the preceding claims, wherein at least one temperature sensor is positioned downstream of connectors to isolate error signals emanating from the connectors.

5. A method as claimed in claim 4, wherein a thermistor or thermocouple is located down the optical fibre to provide a temperature indication and avoid or allow for the influence of connector error.

6. A method as claimed in claim 5, wherein said thermistor or thermocouple is located 20 m down the optical fibre.

7. A method as claimed in any one of the preceding claims, wherein the wavelength of the transmitted signal between the ultraviolet and infrared spectrum is in the range 780 to 785 nm.

8. A method as claimed in any one of the preceding claims, wherein the transmission power of the laser is less than 10 W.

9. A method as claimed in any one of the preceding claims, wherein the transmission power of the laser is less than 1 W.

Dated this 27th day of September 2002
CRC FOR INTELLIGENT MANUFACTURING SYSTEMS & TECHNOLOGIES LTD
By their Patent Attorneys
GRIFFITH HACK
Fellows Institute of Patent and
Trade Mark Attorneys of Australia

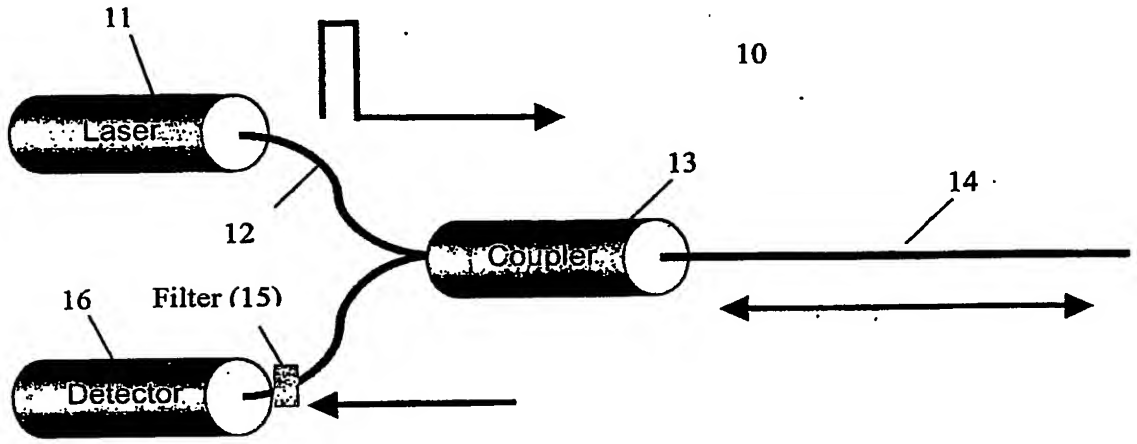
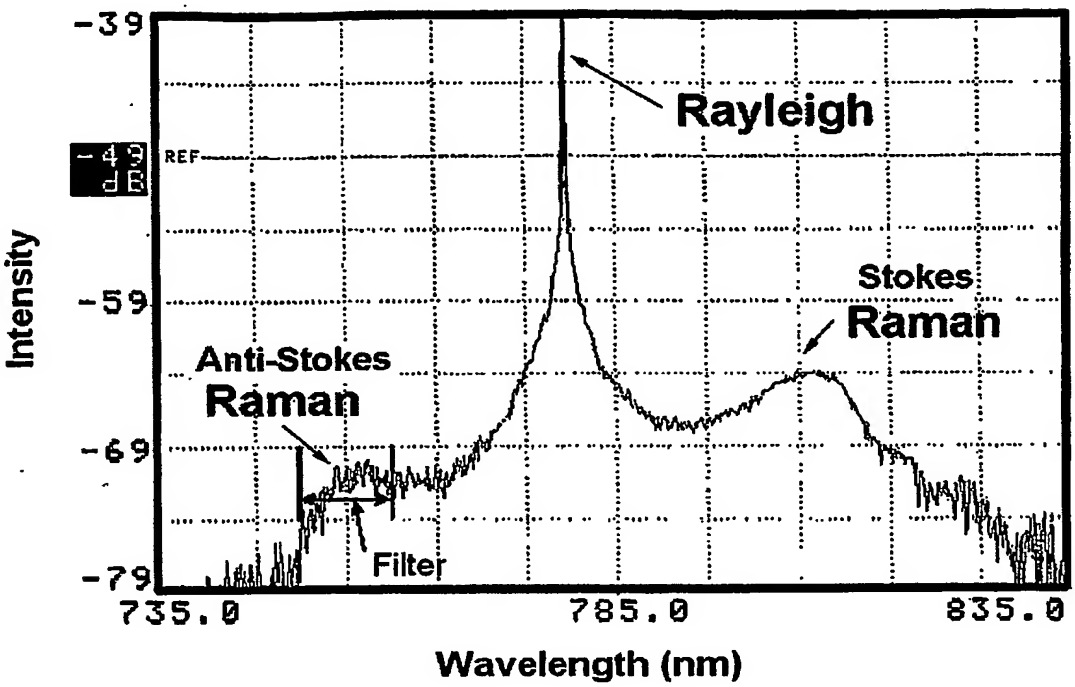


Figure 1.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REF
-49
dB
-59
-69
-79
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Stokes
Raman
Anti-Stokes
Raman
Filter
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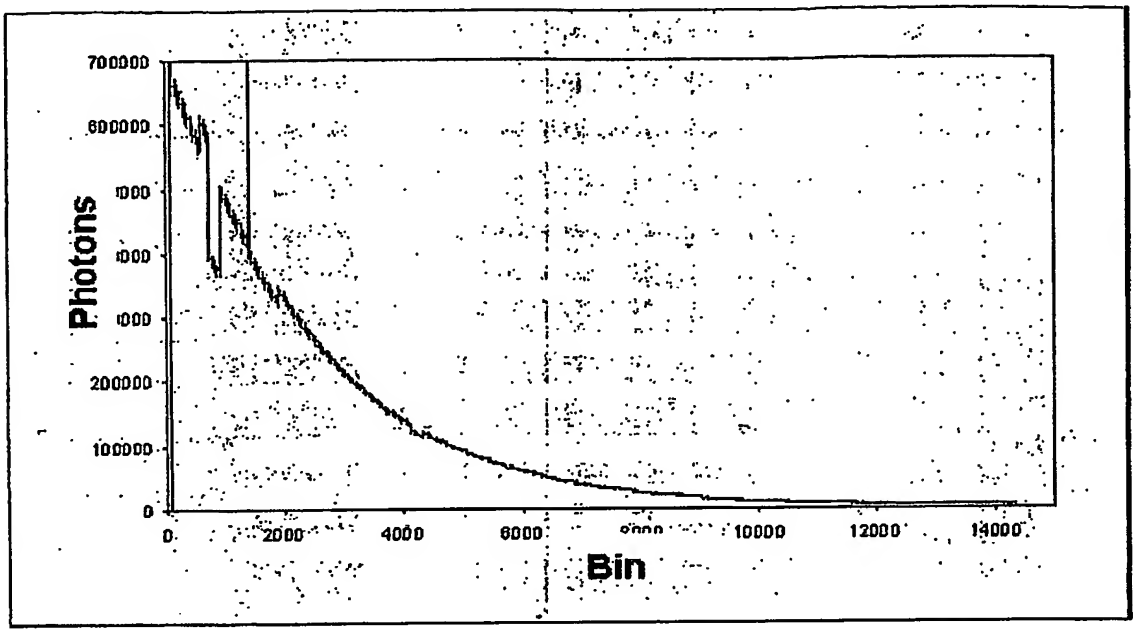
785.0
835.0
Wavelength (nm)

Figure 2.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600000
Photons
200000
100000
0
0
2000
4000
6000
10000
12000
Bin

Figure 3.

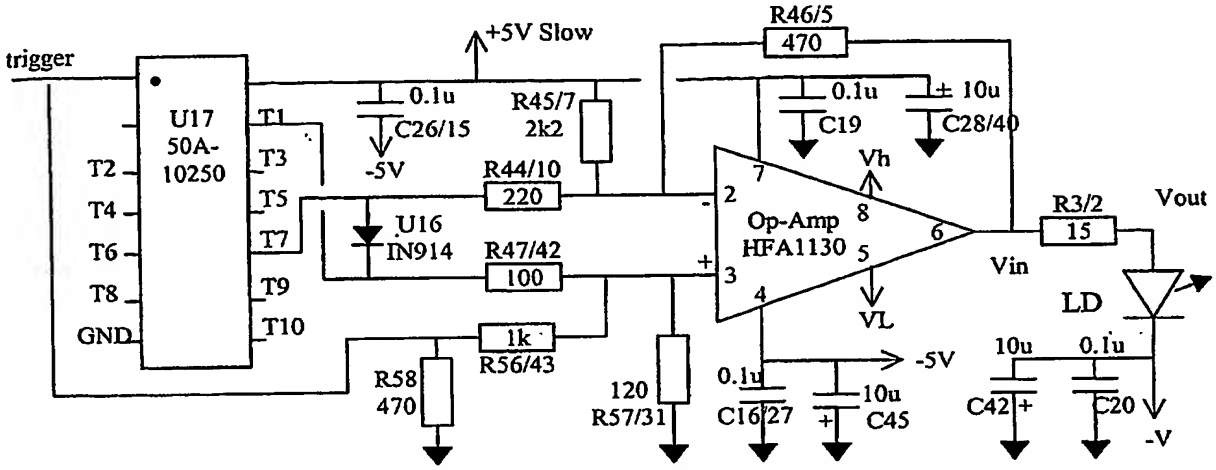
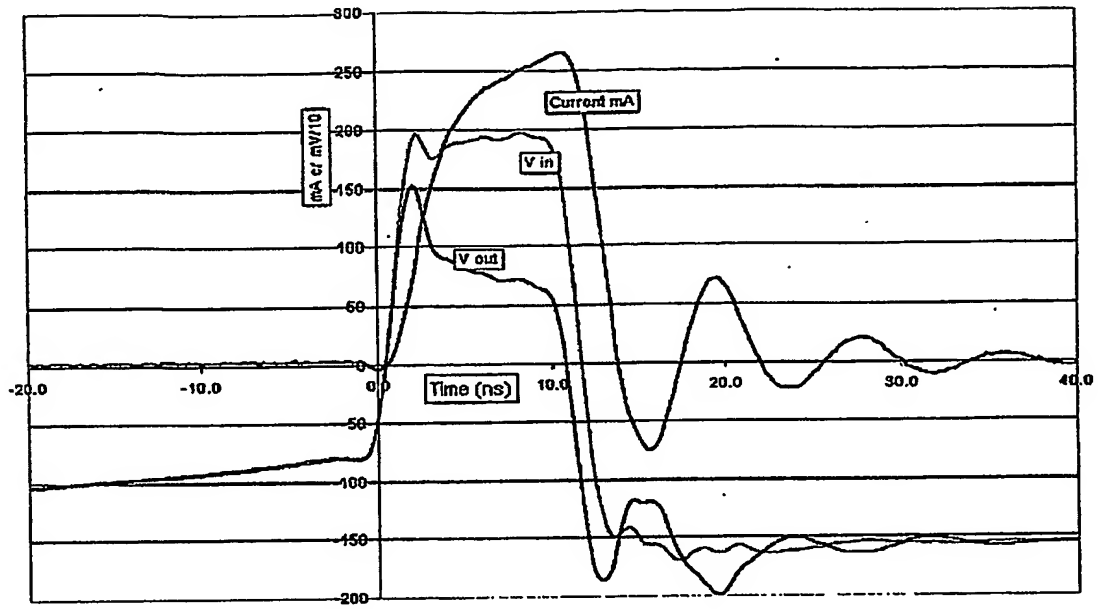

trigger
U17
50A-
10250
T1
T2
T3
T4
T5
T6
T7
T8
T9
GND
T10
+5V Slow
0.1u
C26/15
-5V
R45/7
2k2
R44/10
220
U16
IN914
R47/42
100
1k
R56/43
R58
470
120
R57/31
R46/5
470
0.1u
C19
± 10u
C28/40
Vh
Op-Amp
HFA1130
VL
Vin
R3/2
15
Vout
LD
-5V
0.1u
C16/27
10u
C45
10u
C42
0.1u
C20
-V

Figure 4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250
200
150
100
50
0
-50
-100
-150
-200
mA or mV/10
Current mA
V in
V out
-20.0
-10.0
0.0
Time (ns)
10.0
20.0
30.0
40.0

Figure 5

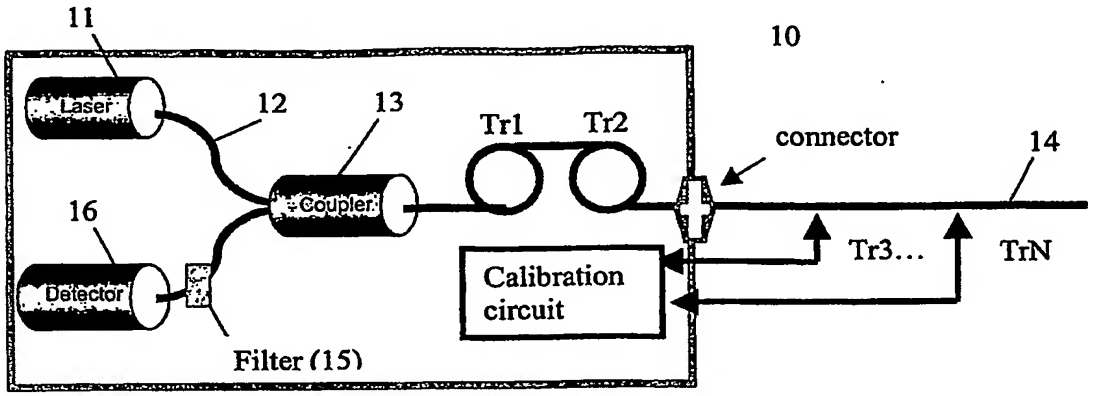
11
10
Laser
12
13
Tr1
Tr2
connector
14
16
Coupler
Tr3...
TrN
Calibration
circuit
Detector
Filter (15)

Figure 6

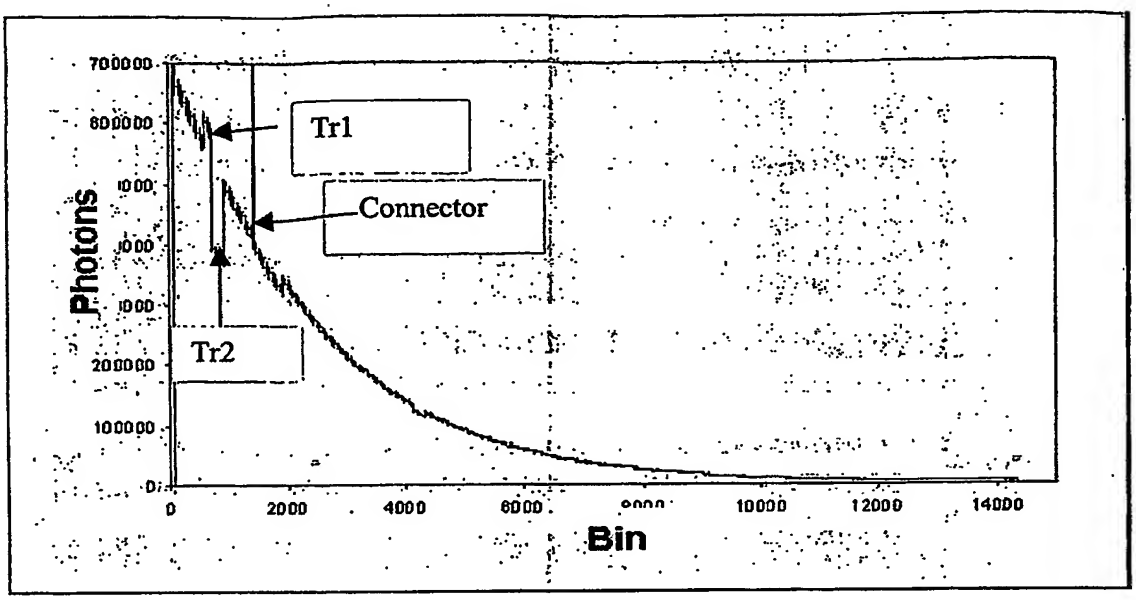
700000
600000
Photons
200000
100000
Tr1
Connector
Tr2
0
2000
4000
6000
10000
12000
14000
Bin

Figure 7